Using Ocean Acoustics to Improve Large Shallow-water Soliton Simulations

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Abstract*-Large amplitude ocean solitons can interfere with underwater acoustic signals that pass through the solitons. This can disrupt underwater acoustic communications and produce erroneous measurements in ocean acoustic experiments. Recently a simulation method has been developed that links certain properties of the soliton with properties of the affected acoustic signals. This can be used as a "feedback method" to determine if acoustic signals are likely to be affected in ocean regions where solitons may be present. Results from ocean model and acoustic model simulations are given to illustrate the method.

I. INTRODUCTION

Ocean solitons can affect the magnitude and phase of acoustic signals that travel through them. The effects can range from slight to severe and are very unpredictable. Intermittent disruptions in ocean acoustic signals have been observed for many decades and were often attributed to interference caused by internal waves and ocean solitons. Until recently there were no simultaneous ocean and acoustic measurements taken to support the assertions. Recent advances in computer modeling have made it possible to simulate both the evolving ocean solitons and the acoustic signals that pass through them. Using this approach computer simulations have been used to predict the large-scale effects on the acoustic signal [1]. The typical sequence of events requires that a nonlinear, nonhydrostatic, primitive equation ocean model be initialized by tidal velocity and density, and used to estimate the changes in the environmental parameters due to soliton creation and propagation [2]. These changes in the environmental parameters are used to calculate the related changes in the ocean sound speed field. The last step in the sequence is to run an ocean acoustic computer model to simulate the propagation of the acoustic signal through the estimated sound speed field and predict the changes in the acoustic signal. Typical tidal velocities in a particular region may be obtained from historical records. Often, the tidal velocity is not precisely known and assumptions have to be made from a number of possible values. Any variations in the tidal velocity require that the time consuming sequence of computer simulations (from both ocean model and acoustic model) be repeated. Recently, we have demonstrated a possible way of estimating the soliton structure that could significantly affect the acoustic signal. This estimation is made before any ocean model simulation is made. This can greatly reduce the number of computer simulations since only ocean model simulations are made for those conditions that might significantly affect the acoustic signal. In principle, only a single ocean model simulation followed by a single acoustic model simulation is required to substantiate the prediction. This acoustic "feedback" method is described in this article and examples are shown that illustrate the method. The possible use of Fourier-like decompositions using cnoidal functions is also discussed as a means of providing a better estimation of the soliton structure that could affect the acoustic signal.

II. THE FEEDBACK METHOD

The feedback method is an acoustic analysis to pre-determine what combinations of acoustic frequencies and source depths might be affected when the corresponding acoustic signal passes through and interacts with an ocean soliton packet of specific physical dimensions. It should be most applicable to ocean regions that have a history of soliton creation and propagation. This would include ocean regions near shelf breaks and other sharp sea floor discontinuities. The feedback method can be useful as a pre-assessment tool, to determine what acoustic frequencies and source depths to avoid; or, as a post-assessment tool to estimate if solitons were responsible for acoustic signal losses and to estimate the dimensions of the offending soltion packets.

A description of the feedback method follows:

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(1) Determine the key environmental parameters for the ocean region that will be traversed by the acoustic signal. Typically these parameters are the sea floor depth, bathymetry, thermocline depth, ocean sound speeds above and below the thermocline, and ocean bottom-subbottom sound speeds and attenuations.

(2) Select the desired acoustic frequency, and calculate the number of acoustic modes, mode shapes, wavenumbers (k_n) and bottom attenuations (α's) for each mode.

(3) Select an acoustic source depth and calculate the acoustic modes that are excited and their associated k_n values. This is a quick calculation by a normal mode model, but it is necessary to calculate accurate mode values to several significant figures.

(4) Calculate the difference in adjacent acoustic wavenumbers, $k_n - k_{n-1}$, for the excited acoustic modes.

(5) At the mean depth of the thermocline decompose the simulated ocean soliton into its horizontal wavenumbers, K_M .

(6) The condition for energy exchange between acoustic modes due to interaction with the soliton is $K_M = k_n - k_{n-1}$. Is this condition fulfilled for any allowable values of K_M and k_n ? If the answer is "No," then little or no acoustic interactions will occur with the soliton at the chosen source depth and frequency. No further analysis is needed and the remaining steps can be ignored.

If the answer is "Yes," then it is possible that an acoustic interaction will occur with the soliton resulting in acoustic mode conversions. However, it is also possible that the acoustic mode conversions will not be detrimental to the acoustic signal.

(7) To determine if the acoustic mode conversions will be detrimental, calculate the bottom attenuation, α, for affected modes to see if $\alpha(k_n)$ is significantly different from $\alpha(k_{n-1})$. If the α's have nearly the same magnitude, mode conversions are not harmful to acoustic signals. No further analysis is needed and the remaining steps do not need to be followed.

(8) If the α's are significantly different, lower-to-higher mode conversions may affect the acoustic signal. To avoid the possible detrimental effects to the acoustic signal, choose a different source depth and/or source frequency and perform steps (2) through (7) again. There should be a large number of source frequency-depth combinations that are not affected by the ocean soliton, and only a few that are affected.

Typically the ocean modeler makes many simulations from all likely values of initial parameters (e.g., tidal velocities, initial densities, bathy). This allows a prediction of the possible structure of the internal waves and solitons. Then an acoustic model is used to propagate the acoustic signal through the simulated soliton fields, and the acoustic results are examined to see if the acoustic signal could be affected. By first knowing the K_M's that could affect the acoustic signal, the ocean modeler can greatly reduce the number of possible simulations by concentrating only on ocean parameters that could produce solitons with those K_M values. If none are possible, no further ocean model simulations need be made since the acoustic signal will not be affected by the probable solitons. If there are solitons that do have the particular K_M values, then ocean simulations are made and acoustic models used to propagate the acoustic signal through the simulated soliton fields, thus, validating the original prediction made by the *a priori* acoustic analysis.

The "feedback method could be used for inverse measurements and calculations in the following way.

(1) Make acoustic measurements over several frequencies in ocean regions where solitons are known to exist.

(2) From the acoustic measurements determine what acoustic frequencies appear to be diminished more than would be expected. This observation should be straightforward since large abrupt losses in acoustic signal over a narrow frequency band is unusual.

(3) From this knowledge and a knowledge of the waveguide parameters (e.g., water depth, bottom composition, topography) the K_M of the suspected soliton could be estimated. Satellite observations could be used to help validate the prediction.

III. Simulation Region

In order to illustrate the feedback method an ocean region was chosen where solitons had been observed and computer simulation studies had been performed [2]. The region chosen for this simulation study was located south of the Shandong peninsula and will be referred to as the Shandong region. Fig. 1 shows a color contour indicating the ocean depths in the region [2]. The color scale gives the ocean depth in meters. The arrow shows the direction of a typical solitary wave train. Similarly, solitary wave trains have been observed by satellite SAR imagery. The beginning of the arrow indicates an area of relatively steeper slope. This is a location where the first internal bores had been observed in our earlier simulations [2].

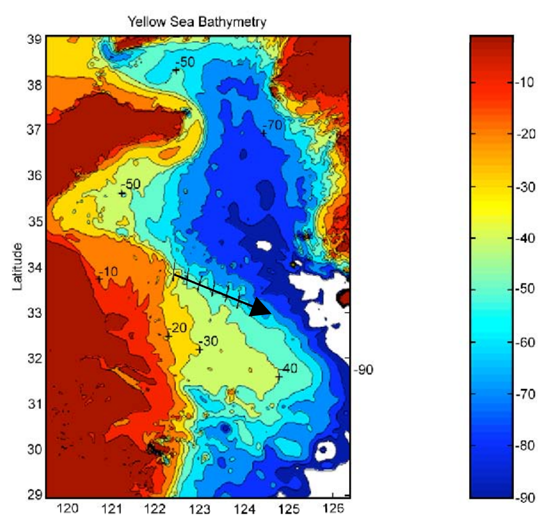

Fig. 1 Ocean depth in the Shandong peninsula region.

IV. Ocean Model

The Lamb (1994) model [3] was used for simulating the generation and propagation of internal solitary waves. This model

solves the incompressible Boussinesq equations on a rotating *f*-plane. In the along-bank direction (i.e., *y*-direction), the velocity, *v*, is included but the derivative with respect to the *y*-coordinate is not included (hence, the designation of a "2.5 dimensional" model or representation). The key equations of the model are:

$$V_t + V \bullet \nabla V - fV \times \hat{k} = -\nabla P - \hat{k}\rho g\,, \tag{1}$$

$$\rho_t + V \bullet \nabla \rho = 0\,, \tag{2}$$

$$\nabla \bullet V = 0\,, \tag{3}$$

where viscosity is neglected, $V(u, v, w)$ is the velocity vector, ∇ is the three-dimensional vector gradient operator, subscript t denotes the time derivative, ρ has been scaled by the reference density as well as P after the hydrostatic pressure in balance with ρ_0 has been subtracted off, i.e., the physical density is $\rho_0(1+\rho)$, and the physical pressure is $\rho_0(P-gz)$, g is the gravitational acceleration, f is the Coriolis parameter taken as 5.2×10^{-5} s^{-1} for a latitude of 21 degrees, and $\hat{k}$ is the unit vector along the *z*-direction. In the three-dimensional equations (1)–(3) the partial derivatives with respect to *y* are neglected, i.e., $\partial(\bullet)/\partial y=0$; thus, Equations (1)–(3) are equivalent to Equations (1a)–(1d) in Lamb's 1994 paper [3]. The *y*-component $v(x, z)$ of the model is in geostrophic balance with the horizontally varying density field.

Before the equations are solved, they are transformed to a terrain following coordinate system (sigma-coordinates) in the vertical, which leads to higher vertical resolution over the region where the solitons are formed. The equations are solved over a domain bounded below by the topography and a rigid lid above.

V. Tides, Hydrography, and Parameters

The dominant barotropic tidal component in the Yellow Sea is the semidiurnal M2 tide. In the Shandong area, there are pronounced flood and ebb tides. The flood tide component shows a structure that is indicative of a dividing line between tidal ellipses that are cyclonic in the northern part of the Shandong region and anti-cyclonic in the southern part. Along the shore the tidal magnitude variability ranges from 1.2 m/s to .3 m/s, Warn-Varnas et al. [2].

For the Shandong region, hydrography surveys were not available. As a result the monthly averaged temperature and salinity surveys distribution from the National Oceanographic Data Center (NODC) database were used. From the NODC data base, we extracted temperature and salinity profiles for the month of August, the month that RADARSART1 observations showed the presence of solitary waves, Fig. 1.

Simulation parameters are given in Table I, where h_d is pycnocline depth, H water depth, V_t is tidal strength, and d_h is the length of the computational domain.

TABLE I
SIMULATION PARAMETERS

Case	h_d (m)	H (m)	V_t (m/s)	d_h (km)
1	15	70	0.70	240
2	15	70	0.35	240
3	15	70	1.20	150

Case 1 was tuned to SAR data [2]. For this case, the pycnocline was at a depth of 15 m, a peak barotropic tidal velocity of 0.7 m/s was used, and the water depth was 70 m. The density was specified on the basis of climatology. Each tidal cycle generated a wave propagating on the shelf and a wave propagating away from the shelf. At 71 hours there were four solitary wave trains propagating away from the shelf and another one forming at about 50 km from the shelf. These are indicated by the density contrast in Fig. 2.

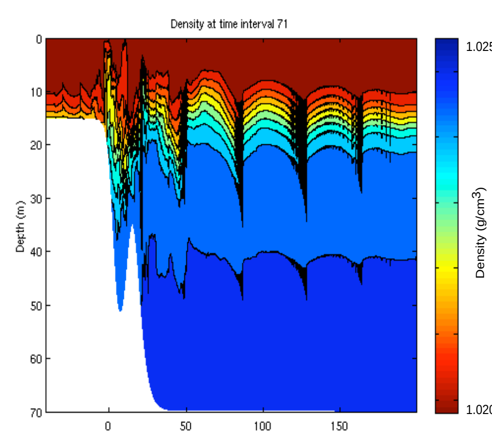

Fig. 2 Contour plot showing density contrasts in range and depth for hour 71 of solitary wave simulations.

VI. Acoustic Simulations

Salient environmental parameters were chosen from the simulated environment shown in Fig. 2. The mean thermocline depth (15 m) and the typical sound speeds above and below the thermocline were used to create a two-layer model to illustrate the feedback method. The actual contour along the thermocline was extracted and used as the internal boundary separating the two layer-model. This is shown in Fig. 3 where the upper figure (a) is the same as Fig. 2, but rotated 180 degrees about the vertical. The lower figure (b) shows the resulting two-layer model with two soliton packets along the

thermocline. The red dot indicates the location of a hypothetical acoustic source for the acoustic analysis of the problem.

The reduction of the complex environment shown in Fig. 3(a) into the simpler two-layer problem shown is Fig. 3 is part of the feedback method. The two-layer problem retains only the important acoustic mode structure while allowing for a realistic, but simpler representation of the nonlinear soliton packets. Brute force acoustic model simulations of each environment (i.e., Fig. 3(a) and 3(b)) produced the same acoustic losses. In the brute force approach an acoustic model [4] was used to propagate the acoustic signal through the simulated soliton fields shown in Figs. 3(a) and 3(b). A different acoustic model run was required for each of the frequencies of interest. For a large acoustic bandwidth this could require hundreds of model runs.

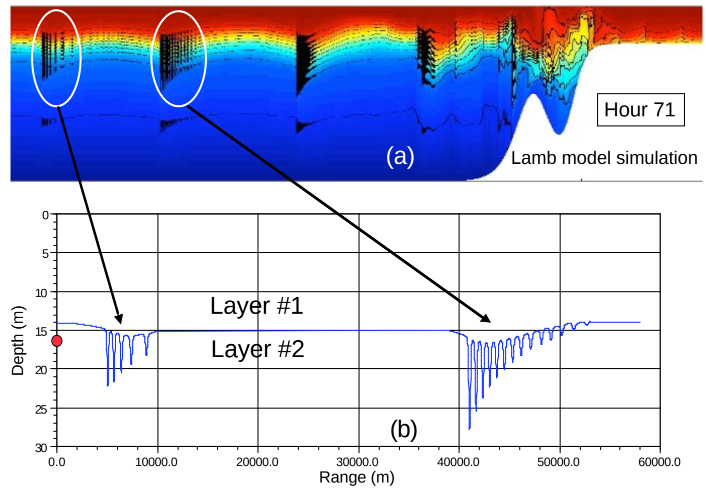

Fig. 3 The upper figure is Fig. 2 rotated 180 degrees about the verticle. The lower figure is a two-layer model of the two soliton packets shown.

A color contour plot showing transmission loss in decibels (dB) as a function of range and depth for three frequencies of interest (250, 275 and 300 Hz) is shown in Fig. 4. It was obtained by the brute force approach. Red gives the smallest loss; blue gives the greatest loss.

The acoustic results shown in Fig. 4 are typical of the so-called "anomalous resonant" effect caused by solitons interacting with the acoustic field [5]. Within a narrow band of frequencies, in this case 250 - 300 Hz, an abrupt signal loss occurs. The loss of signal is attributed to mode conversion, i.e., energy transferring from a lower-order acoustic mode to an adjacent higher-order acoustic mode. The mode conversion results from the interaction of the acoustic signal with the soliton packet. For a substantial signal loss to occur, as shown in Fig. 4, another condition is necessary [1]. The lower-order mode must be initially propagating most of the acoustic energy and this mode must have a smaller ocean bottom attenuation associated with it. The adjacent higher-order mode that receives the energy must have a larger ocean bottom attenuation associated with it. The large signal loss occurs some distance (range) from the soliton because the larger ocean bottom attenuation has greatly damped the acoustic field over that distance. Thus, it is mode conversions into modes with larger ocean bottom attenuations that actually produce the "anomalous resonant" effect [1]. This is seen in Fig. 4 where the initial soliton interaction occurred at approximately 5 - 10 km in range, and the significant signal loss occurred after 60 km in range. The higher-order mode had an ocean bottom attenuation five times larger than the lower-order mode. As discussed above, the condition for strong energy exchange between the acoustic modes due to interaction with the soliton is $K_M = k_n - k_{n-1}$. In Fig. 4 this condition is met for an acoustic frequency of 275 Hz, but not for frequencies of 250 Hz and 300 Hz. A better understanding of the mode conversions can be achieved by examining the acoustic mode structure for the three cases shown in Fig. 4. The mode structure was obtained by performing a Fourier decomposition of the acoustic field.

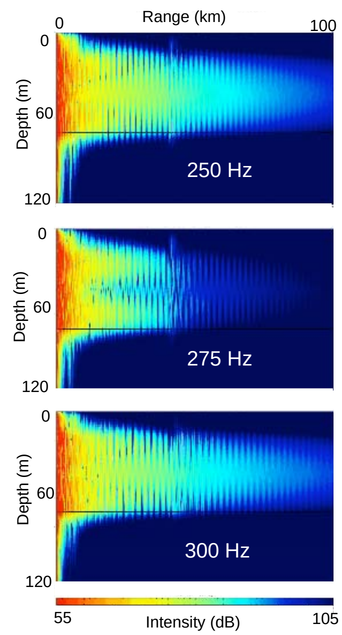

Fig. 4 Transmission loss at three adjacent frequencies.

The four plots shown in Fig. 5 are the result of Fourier decomposition of the pressure field at range of 60 km and source depth of 18 m. Fig. 5(a) is the result of a decomposition at a frequency of 275 Hz on an environment that does *not* have the interface oscillations due to the internal wave, i.e., it is a range independent environment. Fig. 5(b) is the result of the decomposition on a 275 Hz case with the soliton oscillations present. (Note the difference in the *y*-axis scale). Fig. 5(c) and Fig. 5(d) also have the soliton oscillations present. Fig. 5(c) and Fig. 5(d) are decompositions of the acoustic field for acoustic source frequencies of 250 Hz and 300 Hz, respectively.

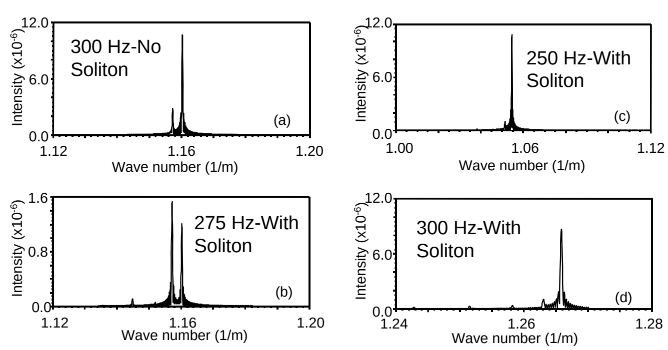

Fig. 5 Decomposition of the acoustic field into wave numbers: (a) 275 Hz with no soliton; (b) 275 Hz, (c) 250 Hz, and (d) 300 Hz with the soliton.

The use of the two-layer model at the chosen range of 60 km has two advantages: the mode structure is less complicated and due to damping only those modes that are dominant (i.e., carry significant energy) survive at 60 km. In Fig. 5(a) where there is no soliton, the first mode carries most of the energy with the second mode carrying only a fraction of the energy. This is the same situation with the soliton packet for frequencies of 250 Hz (Fig. 5(c)) and 300 Hz (Fig. 5(d)). However, at the "resonant" frequency shown in Fig. 5(b), the second mode carries the most energy with the first mode carrying less. Mode conversion has occurred in the 275 Hz case due to interactions with the soliton. The second mode had an ocean bottom attenuation five times larger than the first mode. This explains the loss of energy shown in Fig. 4(b) and the smaller intensity shown in Fig. 5(b).

It should be noted that the ideal conditions that produced the dramatic signal loss shown in Fig. 4 are rare in the dynamic, fluctuating ocean environment. Rather, a fluctuating and less dramatic signal loss would be expected. However, the physical processes that produced the large signal loss shown in Fig. 4 should be present in the real ocean environment. The feeback method is an attempt to predict the worst-case scenario.

Two mode decompositon techniques were used to obtain the mode structures shown in Fig. 5: Fourier decompostion and inverse scattering transform decomposition (STD) [6]. The latter was first introduced by Osborne [7]. The two techniques gave the same decomposition values for the example shown in Fig. 3. Had the evolution of the soltion packets been longer (> 71 hrs.), the STD technique would likely be the one of choice. This would be due to the soliton packets evenually evolving to a KdV-like structure. The STD technique has the advantages that it decomposes the soliton wave field into fewer significant modes, and it preserves information about the evolution of the solitary wave packet -- neither of this is done in a Fourier decompostion.

VII. Illustration of the Feedback Method

The feedback method is an attempt to "reverse engineer" the analysis given above, without making the brute force analysis. The feedback method was used to predict the "anomalous resonant" frequency of 275 Hz as illustrated in Fig. 4 without making any computer model runs. As in Step (1), above, the key environmental parameters for the ocean region were determined. These were the same environmental parameters of the two-layer environment, but without the soliton packets along the interface. Following Step (2), the acoustic modes, mode shapes, wavenumbers, and ocean bottom attenuations were calculated for acoustic frequencies of 250, 275, and 300 Hz. The frequency band where signal losses would occur would not be known in an actual application. Thus, it would be necessary to perform the calculation over a very large band of frequencies, e.g., bandwidths as large as a kilohertz. In Step (3) the same acoustic source depth was chosen as shown in Fig. 4. From the mode shapes (amplitudes) the modes that could be excited at that source depth for each of the three frequencies were determined and the associated ocean bottom attenuation for each mode was noted. The difference in attenuation for the adjacent modes was also noted. Wavenumber differences (k_n - k_{n-1}) for adjacent excited modes were calculated. These differences represented the possible horizontal wavenumbers of a soliton packet, K_M , that could produce acoustic mode conversions. And, the mode conversions with large differences in their attenuations could produce large acoustic signal losses. The horizontal wavenumber, K_M, that fulfilled these criteria for an acoustic frequency of 275 Hz was one of the two dominant wavenumbers contained in the first soliton packet shown in Fig. 3. Knowing the possible values of K_M, an ocean modeler could determine if that value were possible before running his ocean model and producing the soliton simulations. Or, conversely, he could use that value of K_M to produce the corresponding soltion representation and the acoustic model applied to verify that large signal losses were possible.

VIII. Conclusions

A feedback method has been developed that can indicate if large ocean solitons are likely to adversely affect ocean acoustic propagation. It is an approximate method that uses acoustic analysis to pre-determine what combinations of acoustic frequencies and source depths might be affected when acoustic signals propagate through and interact with large ocean soliton packets of specific physical dimensions. The feedback method can be useful as a pre-assessment tool, to determine what acoustic frequencies and source depths to avoid; or, as a post-assessment tool to estimate if solitons were responsible for acoustic signal losses and to estimate the dimensions of the offending soltion packets.

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